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Use of dual planar jets for the reduction of flow-induced noise

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The planar jet has been proposed to reduce the flow-induced noise. However, the self-noise emission from a single planar jet is a limiting factor on the performance based characteristics of this technology. Therefore, this research paper reports an alternative dual planar jets geometry in an attempt to minimize the self-noise of the single planar jet, thus, further enhancing total noise reduction in the application. Tandem cylinders are considered as the generic bluff body, which represents the source of flow-induced noise. Tests are conducted to capture noise reduction effects when using a single planar jet geometry. Subsequently, two different configurations of the dual planar jets geometry were tested in comparison. It is observed that the dual jets geometry achieves more noise reduction when compared to the single jet. Moreover, conclusions are made on the most efficient configuration in the dual jets geometry. [http://dx.doi.org/10.1063/1.4976336]

I. INTRODUCTION

Flow-induced noise potentially causes disturbance and annoyance within various engineering applications.[1–6] In particular, airframe noise, which is generated through the interaction between the turbulent flow and the solid bodies on the aircraft, has been identified as an "aircraft noise barrier" since the early seventies.[7] Therefore, considering the interdisciplinary challenge between fluid mechanics and acoustics arising from this noise effect, airframe noise reduction has become a major concern for stakeholders within the aviation sector, acoustic experts, fluid mechanics engineers and researchers.

A recent noise reduction technology–air curtain, also referred to as the planar jet, has been proposed to reduce flow-induced noise.[8–11] When applied within the aerodynamic field of an aircraft, this technology is designed to reduce landing gear noise at take-off and approach. The fundamental concept is to install an upstream planar jet to shelter the noise generating source, i.e.the bluff body, thereby deflecting the incoming flow. Due to the shelter effect, the flow speed originally impinging on the bluff body can be significantly reduced, therefore, a reduction of the flow-induced noise can be achieved. Recent investigations[9,10] have confirmed the validation of this technology. However, it was also observed that the planar jet itself emits a substantial amount of jet noise, herein termed the planar jet self-noise. The planar jet self-noise impedes the implementation of this technology, hence, the suppression of self-noise is highly expected.

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Jet noise emission is a widely studied subject area, particularly in aeronautic and aeroacoustic engineering. It has been found that[12–17] in a quiescent ambient, jet sound intensity is highly correlated with the jet speed (U_j). More specifically, due to the existence of monopole, dipole and quadrupole sources, jet noise sound intensity scales with ($AU_j^4 + BU_j^6 + CU_j^8$), where A, B and C are complex functions depending on the flow conditions, e.g. temperature and turbulence intensity of the jet. In addition, for a subsonic jet, noise dominantly arises from blowing effect towards the jet nozzle edges (classic lip noise theory).[17–19] As such, one more term, U_j^5 is also introduced. Once there is a crossflow, the jet interacts with this, and consequently, jet noise emission increases to a large extent when compared to the quiescent flow.[10] In this paper, a proof of concept study is reported, where the geometry of dual planar jets is proposed to suppress self-noise and achieve greater flow-induced noise reduction.

II. DUAL JETS HYPOTHESIS

The jet used for the single jet geometry and the downstream jet utilized for the dual jet geometry are henceforth termed as 'primary jet', while the upstream jet for the dual jets geometry is termed as 'upstream jet'. Dual jets in crossflow have been found to be much different from the single jet.[20–22] More specifically, when the extra upstream jet is introduced, these jets merge along the deflection region as a result of interaction with the crossflow, the trajectory and the edge of the primary jet become elevated. Fig. 1 illustrates the related dual jets and the single jet geometries. A 2D Cartesian coordinate system is established and utilized throughout this article, where the origin coincides with the center of the primary jet outlet. The primary jet trajectory is also marked within each schematic, shown as a streamline passing through the origin. In Fig. 1(a), x_0 is an arbitrary horizontal position, while the corresponding height of the jet leeward edge, which determines the maximum shelter given to the bluff body located downstream, is y_0. As shown in Fig. 1(b), the upstream jet deflects the crossflow, thereby protecting the primary jet. Thus, the primary jet leeward edge is elevated. Note that the primary jet speed in Fig. 1(a) and (b) are equal, termed as U_{p1}. Speed of the upstream jet is U_{u1}, and $U_{u1} < U_{p1}$. Therefore, an initial hypothesis can be drawn that the dual jets geometry could lead to a lesser noise emission from a bluff body located downstream of the set-up, when compared to the single jet geometry. Potentially, the elevated leeward edge provides an improved shelter for the bluff body, thereby achieving more noise reduction. Also, interaction noise between the crossflow and the primary jet is much lower due to further protection by the upstream jet. Finally, since the upstream jet possesses lower speed, the self-noise becomes far lesser than the primary jet, and as such, less overall noise emission is anticipated.

More importantly, a second hypothesis can equally be made based on a second configuration of dual jets geometry. The idea is to maintain the shelter height in the dual jets geometry as same as that in the single jet geometry by reducing the speed of both primary and upstream jets, which can obviously result in far more suppression of the jet self-noise. The second configuration is illustrated in Fig. 1(c), with U_{u2} and U_{p2} to be the speed of two jets. Note that $U_{u2} < U_{u1}$ and $U_{p2} < U_{p1}$.

All three configurations were tested with flow-induced noise reduction effects as the core objective. These are denoted as Single, Dual1 and Dual2 herein, shown in Fig. 1. The experimental rig, set-up and results are reported in the following sections.

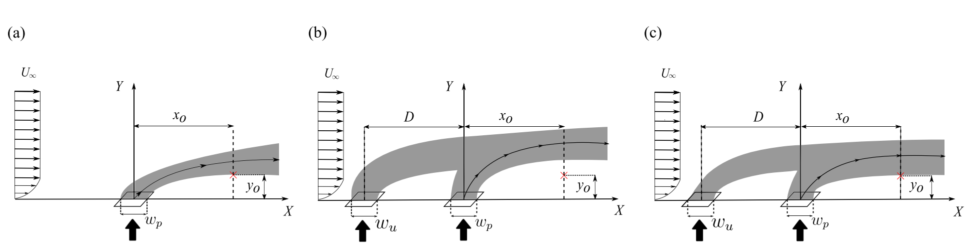

FIG. 1. Planar jets in a crossflow:(a). Single; (b). Dual1; (c). Dual2.

III. EXPERIMENTAL RIG AND SET-UP

Experimental investigations in this study were carried out in a rig within the Fluids, Acoustics and Vibration Lab of Trinity College Dublin. As illustrated in Fig. 2 in both 2D and 3D views, the experimental rig consists of a low-speed open-jet wind tunnel, a planar jet generator and a test platform. A microphone array was attached to the top of the platform in order to conduct acoustic measurements. The entire system was rigidly supported by aluminium extrusion frames.

The open-jet wind tunnel was powered by a $5.5kW$ centrifugal blower providing a crossflow with a maximum speed of $70m/s$, having an outlet size of $75mm \times 75mm$. The turbulence intensity of the free stream was within 2%. The planar jet generator was operated by a $2.2kW$ centrifugal blower, a cubic plenum and a number of jet nozzles. The number of the jet outlet could be managed to be either one or two for specific tests. The jet nozzle outlet was rectangular with a constant spanwise length of $100mm$. The width of the outlet could be modified as required. In the dual jets geometry, the speed difference between two jets were controlled using the metal mesh plate with different porosities. Examples of the mesh utilized in this study are shown in Fig. 2(a).II.

As discussed earlier, a microphone array was mounted on the top of the extrusion frame. The array possesses a planar semicircular shape with a diameter of $600mm$. It was installed parallel to the test platform and equipped with 25 KE 4 Sennheiser electret microphones. One camera was attached to the array center, making noise map superimposed on a real cut-out background. The sampling rate and the sampling time of data acquisition were set as $100kHz$ and $8s$. Results of acoustic measurements are reported in the remainder of this paper, which include one-third octave band spectra of sound pressure level (SPL) and time domain beamforming or noise source localization, i.e. noise map.

IV. RESULTS AND DISCUSSION

Tandem cylinders were utilized as the bluff body and generic noise generating source, supported by two blocks on the platform. The ratio of the pitch and the diameter in the tandem cylinder was controlled to be 3, which was observed to be the configuration that can emit obvious flow-induced noise. A close-up schematic of the set-up is illustrated in Fig. 2. Prior to the acoustic tests, the relative position of the cylinders were optimized based on the single jet geometry. To be more specific, the middle of the tandem cylinder was controlled to be horizontally align with the peak of the jet centreline, but the height of the middle was much lower than the peak to achieve a good shielding. As required by the optimized positioning, X and Y coordinates of the front cylinder were controlled to be 136mm and 28mm respectively. Subsequently, this position was used in all configurations for comparison.

Fig. 3 shows the velocity contour of the CFD simulations for the single and dual jets configurations in this study. These three configurations were selected based on a large number of PIV experiments and CFD simulations. Details were not included in this paper due to the length constraint. In these configurations, the jet outlet width of w_u and w_p were $8mm$ and $10mm$ respectively. The distance

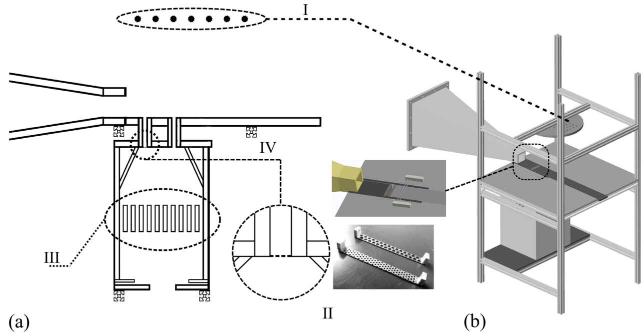

FIG. 2. Schematic of experimental rig (not in scale): (a) 2D View (b) 3D View (I. microphone array; II. jet outlet and mesh for speed control; III. honeycomb structure IV. aluminium extrusion bar).

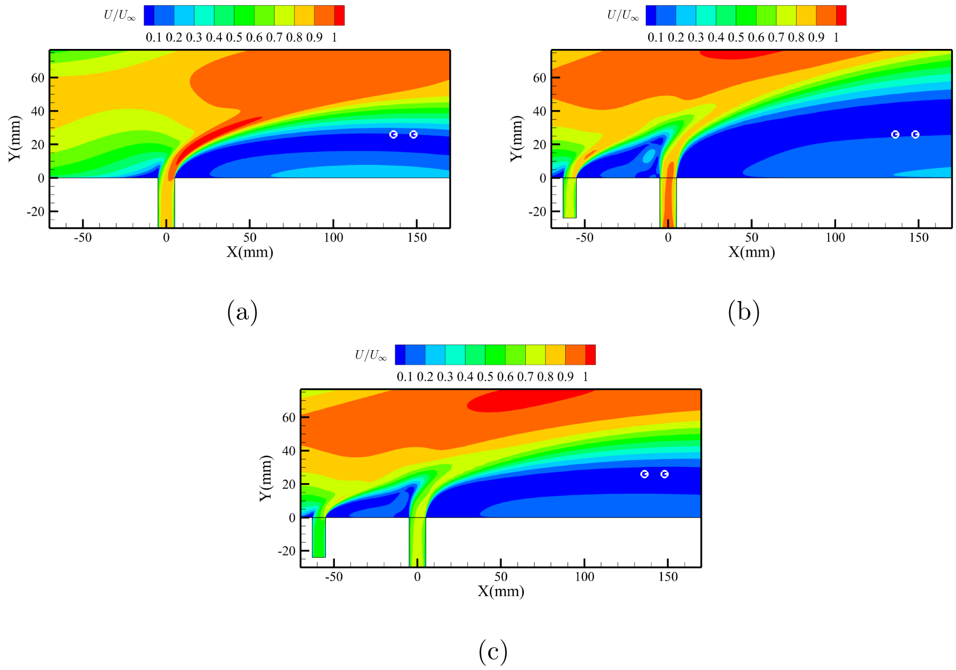

FIG. 3. Flow speed contour: (a). Single (b). Dual1 (c). Dual2.

between the centers of jet outlets (D) was 50mm. The crossflow speed, U_∞ was 50m/s. U_{p1} was 50m/s, and U_{u1} was 40m/s, U_{u2} and U_{p2} were 40m/s and 30m/s respectively. The tandem cylinders diameter and pitch were 4mm and 12mm. The Reynolds number based on the cylinder diameter is 13,235.

In Fig. 3, the cylinders are marked inside with two white circles in scale. It is observed that the cylinders are situated within the low speed flow region in all configurations, showing that the planar jet, either single or dual configurations, can deflect the crossflow and reduce impinging flow speed to the cylinders. It is also observed from the comparison between Fig. 3(a) and (b) that the installation of an upstream jet possessing lower speed and narrow width, elevates shelter height of the initial primary jet. In addition, Dual2 in Fig. 3(c), where the jet speeds are much lower compared to other configurations, provides approximately the same shelter height. As such, these three configurations correspond to those in Fig. 1.

For acoustic analysis, five cases were tested, denoted as BG, Cy, Single, Dual1 and Dual2. BG is the background noise without the cylinders or planar jet. Only a crossflow was utilized for the baseline noise measurement. In Cy, the cylinders are located with an optimized positioning as mentioned earlier. Single, Dual1 and Dual2 are cases with three jet configurations. The cylinders were also installed so as to test noise reduction capabilities.

Fig. 4 shows one-third octave band spectra of test cases acquired from acoustic measurements using the microphone array. Note that these spectra are an average of all microphones in the array rather than one microphone. All five spectra overlap with each other in the frequency range less than 1,250Hz. This suggests that background noise sources, e.g. the wind tunnel blower, dominates within this range and further discussions will not include this low frequency range. Compared with BG, the spectrum of Cy indicates that the cylinders impinged by the crossflow emit substantial noise within a broadband frequency range. A high tone with 107.6dB exists at 2,000Hz. By contrast, the use of a planar jet achieves a quieter result, shown in the spectrum of Single. For example, the high tone is eliminated by the planar jet with an SPL reduction of 14.6dB at 2,000Hz.

Time domain beamforming was carried out for noise map results. Prior to the beamforming, acoustic signals had been filtered using one third octave band filter. Fig. 5 and Fig. 6 show noise maps of Cy, Single, Dual1 and Dual2 in one-third octave bands centered at 4,000Hz and 16,000Hz

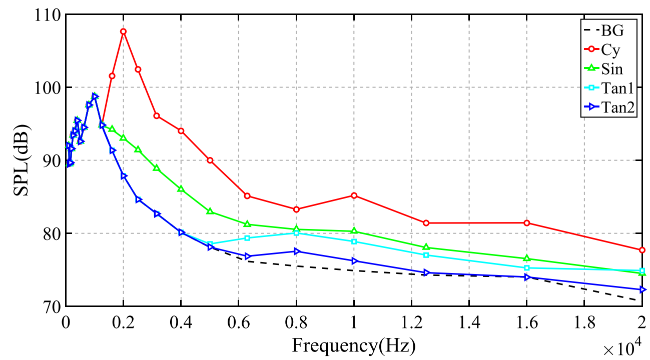

FIG. 4. One third octave band spectra of the SPL.

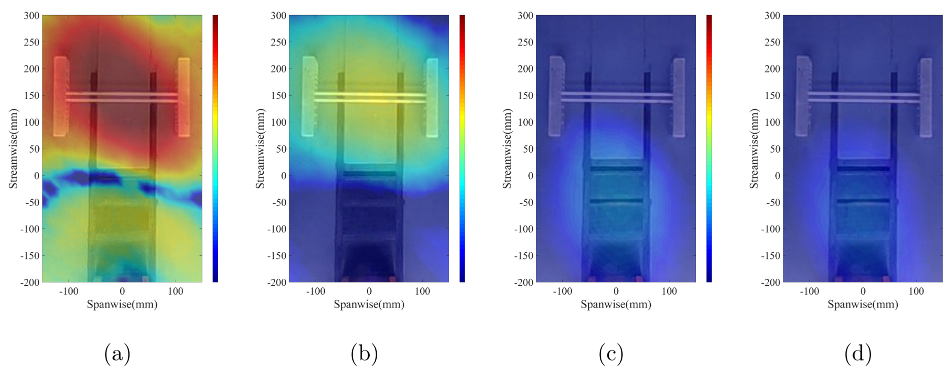

FIG. 5. Noise source map in the 1/3 octave band centered at 4,000Hz (color bar range 10dB)(a). Cy (b). Single (c). Dual1 (d). Dual2.

respectively. From this view, the crossflow blows from the bottom to the top. X and Y axes are spanwise and streamwise respectively. The origin of the coordinate system coincides with the center of the primary jet. Comparison between (a) and (b) in the both figures shows that the use of a single planar jet has the potential to significantly reduce noise emission from cylinders across all frequencies. Fig. 5(b), the cylinders remained a main noise source at 4,000Hz. In contrast, at 16,000Hz in Fig. 6(b), the noise contour peak occurred around the outlet of primary jet, which suggests that the planar jet now becomes the main noise source, and no longer the cylinders.

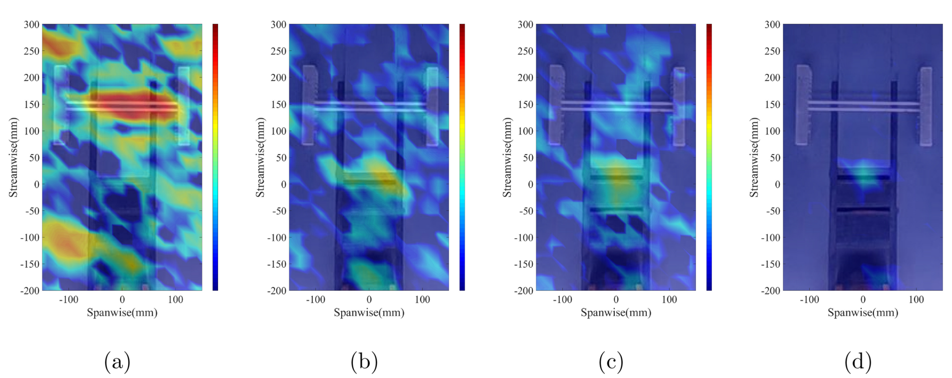

FIG. 6. Noise source map in the 1/3 octave band centered at 16,000Hz (color bar range 8dB)(a). Cy (b). Single (c). Dual1 (d). Dual2.

When two configurations of the dual jets geometry were used, the spectra, shown in Fig. 4 clearly indicates that both configurations can achieve better noise reduction than the single jet geometry. Within (1,250*Hz*, 4,000*Hz*), Dual1 and Dual2 are almost as quiet as BG, i.e. the background noise, suggesting that only a small amount of noise was generated within this frequency range. For frequencies higher than 4,000*Hz*, SPL of dual jets geometry are greater than background noise, although still less than single jet case. To be more specific, SPL of Dual1 is lower than Single except at 20,000*Hz*. Dual2 is quieter than Single as well as Dual1 at all frequencies in this range. Noise reduction improvement is better illustrated in the noise maps. From Fig. 5 (c) and (d) we notice that the subsequent noise emission of the cylinders using single planar jet can be further reduced by the introduction of a dual jets geometry. Regarding self-noise suppression, noise maps at 16,000Hz shown in Fig. 6 (c) illustrates that merely introducing an upstream jet will not obviously reduce primary jet noise. However, the noise map in Fig. 6 (d) shows that the primary jet self-noise is significantly lowered by using Dual2 configuration.

In summery, it is concluded that the dual jets geometry is superior to the single jet geometry for the purpose of reducing flow-induced noise. Furthermore, for the dual jets geometry, the configuration having equal shelter height to the single jet case but lower jet flow speed maximizes the reduction in flow induced noise. It is worth pointing out once more that the position of the cylinders was the optimized one for the single jet geometry. Therefore, we can further anticipate better noise reduction for the dual jets geometry when the position is also optimized for this geometry.

V. CONCLUSIONS AND DISCUSSIONS

Investigations are hereby conducted on the potential use of dual planar jets for the reduction of the flow-induced noise. Tandem cylinders were utilized as the test bodies and as the flow-induced noise source. Three configurations, including single and dual jets geometries, were tested. To locate the cylinders within the flow field so as to be fully shielded by deflection caused by the planar jet, an optimized positioning of the cylinders was found with the help of CFD simulations. For the single jet configuration, despite causing a significant noise reduction, the cylinders and jet itself were identified as the subsequent major noise source within different frequency ranges. Two different configurations of dual jets geometry were tested for further noise reduction studies. Acoustic tests revealed that dual jets geometry were superior compared to single jet geometry when the reduction of the flow induced noise are considered. In the dual jets geometry, the configuration having a shelter height equal to the initial single jet shelter height was found to produce better noise reduction characteristics when compared to the dual-jet configuration having equal primary jet speed as the initial single jet geometry. This further maximizes noise reduction through suppression of the jet self-noise, thereby achieving better overall noise reduction. Therefore, we recommend this dual jet geometry configuration for future implementation.

However, as a proof-of-concept, this technology, in terms of final implementation, requires further investigation on the installation. For example, the cost and the source of the jet flow. Two possible options can be the specialized air blower and the compressed air container. It is expected that the blower can help to achieve a continuous flow rate, but the power supply is needed. By contrast, the flow from the compressed air container can be ejected without power supply due to the pressure difference. However, the flow rate can vary and the container needs to be replaced when the pressure difference is low. As such, design of the rig is highly dependent on the application.

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